A NEW METHOD OF
EVALUATING THE THROUGH-DRYING
CHARACTERISTICS OF POTATOES

by

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INTRODUCTION

Drying is usually defined as the removal of relatively small amounts of water from relatively large amounts of solids into a gas or air stream.

One of the oldest methods of drying is tray or shelf drying. This method involves passing a drying medium over a wet material placed in a tray. A modification of this method is through-circulation drying. This method essentially consists of using a tray made of a material such that the drying air may be blown through the tray and material rather than just over it. For through-circulation drying to be useful, the material must be of a porous nature that will allow air to be blown through it.

Hougen and Marshall (5) state the following advantages of through-drying over tray drying or cross circulation as follows:

1) Through-circulation drying in nearly every instance is much more rapid than the corresponding cross circulation problem. This is the most spectacular difference, because drying times for through-circulation are usually measured in terms of minutes as compared with hours for cross circulation.

2) A continuous drying operation is made possible with through-circulation drying, thus making it suitable for a continuous flow process.

3) The product from through-circulation drying is usually in suitable form for subsequent processing since most operations following drying, such as crushing, grinding or packaging, are performed more readily on a material which has a uniform degree of subdivision.

4) There is generally less labor involved in the operation of through-circulation driers.

5) Since drying time is shorter, the material is not exposed to high temperatures for so long a time.

6) A more uniform product is obtained.

They also state the disadvantage that the pressure drop in through-circulation drying increases power costs somewhat.

With these things in mind the purposes of this investigation were to:

1) Obtain basic data on the through-drying characteristics of wet potato granules for possible use in a pilot plant through-drying process. The main variable being considered was particle size of the granules. The pilot plant through-drier under consideration is one in which wet potato granules would be continuously fed into the top of a cylinder. Drying air would be blown up through the cylinder while an air-lock continuously discharged dried potatoes from the bottom of the cylinder. The necessary data for this proposed drier would be:
    a) Drying rate data (i.e., how fast does a single particle dry). The rate at which the entire mass of granules dries is determined by the psychrometric properties of the air passing through the mass. The rate at which a single particle dries determines how long any single granule must be kept in the drying air.
    b) Data on the length of the "zone of vaporization" (i.e., what would be the minimum length of the drying

cylinder, to keep pressure drop low, such that the portion over which drying occurred would be entirely contained in the cylinder).

2) Evaluate a new method for the determination of drying rates. The classical method of determining drying rates involves some drying process which is periodically interrupted so that weight changes in the sample may be determined. In this study a method was used which is continuous and involves only initial and final moisture content of the material being dried (as far as weight measurements are concerned).

THEORY

The "Zone of Vaporization"

This theory may be developed by the consideration of a perfectly insulated cylinder filled with potato granules (Fig. 1 of Plate I). Nearly bone dry air is fed into the top of this cylinder. This air will have a definite drying effect on the granules with the result that after a given length of time the portion marked A is dry while the portion marked B is still wet. This drying effect operates over a definite portion, Z, of the wet granules and this region is frequently referred to as the "zone of vaporization" (1). Consider this "zone" as arbitrarily divided into four increments dZ_1, dZ_2, dZ_3, and dZ_4.

EXPLANATION OF PLATE I

Fig. 1. Cylindrical bed of potatoes with dry air being blown down through it

A. Dry potatoes

B. Wet potatoes

Z. "Zone of vaporization"

Fig. 2. Temperature gradient existing in bed of potatoes being dried

A. Top of "zone of vaporization"

B. Bottom of "zone of vaporization"

C. Temperature gradient existing if no sensible heat transfer takes place

D. Temperature gradient existing if both sensible heat transfer and mass transfer take place

E. Temperature gradient existing if sensible heat transfer occurs but no mass transfer occurs

PLATE I

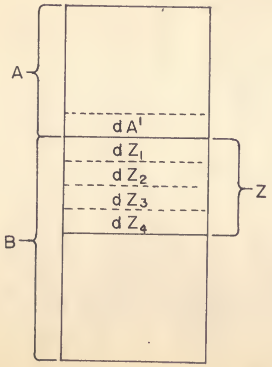


FIG. 1

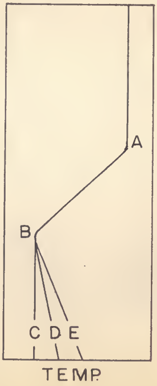


FIG. 2

Temperature Changes Within the Bed

The granules in the increment dA' have just reached an "equilibrium moisture content" such that the vapor pressure of the moisture in the granules, at T_1 (the temperature of the entering air), is in equilibrium with the partial pressure of the water in the incoming air. Since equilibrium now exists between the entering air and the granules in dA', no overall heat or mass transfer will occur as the entering air passes through this portion (dA') or the dried portions above it.

The granules in dZ_1 are almost dry but still contain some moisture which is evaporated on contacting the dry air. This exchange results in evaporation of some of the remaining moisture with a corresponding drop in temperature. The air leaving increment dZ_1 is not yet saturated with the result that some moisture from dZ_2 evaporates causing further cooling. The air leaving dZ_2 is not yet saturated so the process continues until the air leaving dZ_4 is saturated at temperature T_2.

The situation now existing is that shown at point B (Fig. 2 of Plate I). At point B there are cool potatoes and cool saturated air. As the cool air passes further down this column through somewhat warmer granules than at point B, there are two boundary conditions existing, while the actual condition must lie between these two boundary conditions. The boundary conditions are:

1) The cool air will undergo no heat transfer effects and merely pass through the column with no temperature change (line C - Fig. 2 of Plate I).
2) The cool air will be heated due to sensible heat transfer from the potatoes but this heating will not result in mass transfer of water from the granules to the air (line E - Fig. 2 of Plate I).

The actual condition is: The cool air will be continually heated somewhat due to sensible heat transfer from the potatoes. This continual heating will result in an increase in the saturation capacity of the air with the result that there will be some mass transfer of moisture into the air with a corresponding drop in air temperature. The result of this process will be such that at any point the actual temperature will be somewhere between the two boundary conditions as shown in Fig. 2 - line D (Plate I). If there were a sufficiently long bed, the air would leave saturated at the same temperature as the potatoes at the bottom of the bed.

There are several indications that the actual condition discussed above really does exist. The observed temperature gradients along the length of the column are similar to line D - Fig. 2 of Plate I. Also a run was made up to the point where the "zone of vaporization" just started to leave the bed. For this run, the initial moisture content was 57.4 percent. The moisture content of the bottom inch of the bed just as the zone started entering this portion was 55.8 percent. This indicates that a small amount of drying did occur before the "zone" actually entered this portion. On the basis of these data the assumption is made that the amount of drying that occurs below the "zone" is negligible as compared to the far greater amount of drying that occurs in the "zone."

With the assumption that all the drying occurs in the "zone," it is a simple matter to determine the rate of drying. From the preceding discussion, it may be seen that each increment of the "zone" has a certain characteristic temperature. The rate at which any given temperature proceeds down the column is then the rate at which the "zone" itself moves down the column. The drying rate will then be the rate of movement of the "zone" times a factor dependent on the amount of water removed from a section as the "zone" passes through it.

Humidity Changes in Air Passing Through the Bed

A concept that is useful in understanding the discussion to follow involves a relationship between the characteristics of the material being dried and of the drying medium. This concept is one of a "moisture unit," which is defined as that amount of moisture held by the material being dried, which will, at a given flow rate of drying air through the material, cause the air to gain one "humidity unit." A "humidity unit" is defined as a unit measure of humidity in any arbitrarily chosen system of units. For example a "humidity unit" might be one grain of

H_2O per pound of dry air or one pound of H_2O per pound mole of dry air.

It should be pointed out that the amount of moisture constituting a "moisture unit" is not constant but is dependent on the humidity of the air going through the material. For example consider bone dry air at a given flow rate going through a small amount of wet material have three "moisture units" (assume one gm. of H_2O per gm. dry solid is equal to one "moisture unit" in this case). The air passing through this wet material will, by definition, gain three "humidity units." Now consider a case in which the material being dried has the same moisture content but that the drying air is already 70 percent saturated. Since the drying air is no longer bone dry a moisture content of three gm. of H_2O per pound dry solid is no longer three "moisture units," but somewhat less.

The following discussion should clarify this concept somewhat. Consider Fig. 1 of Plate II which represents a bed of wet material with air being blown in from the top. The section A is dry while section B is still wet. Section Z represents the "zone of vaporization" which is broken up in six increments.

The numbers 1, 2, 3, and 4 in the various increments represent the number of "moisture units" arbitrarily assigned to each increment (e.g., for dZ_3, the number "3" indicates that this increment of granules contains enough moisture to add three "humidity units" to air passing through it, providing the air going through it already contains 1 + 2 = 3 "moisture units"

EXPLANATION OF PLATE II

Fig. 1. Cylindrical bed of potatoes with dry air being blown down through it

A. Dry potatoes

B. Wet potatoes

2 A. "Zone of vaporization"

Fig. 2. Plot of humidity of air leaving the bed vs. time for example cited in Theory

PLATE II

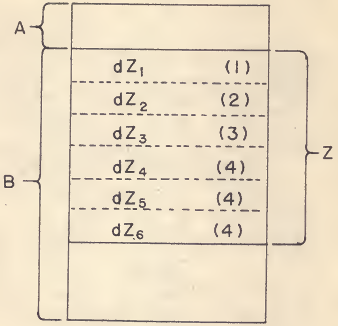


FIG. 1

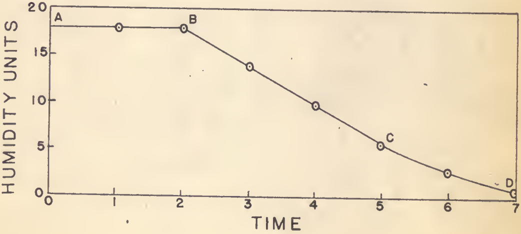


FIG. 2

gained from increments dZ_1 and dZ_2. Similarly, the number "4" for increment dZ_6 indicates that this increment possesses enough moisture to add four "moisture units" to the air providing the air already contains $1 + 2 + 3 + 4 + 4 = 14$ "humidity units" gained from increments dZ_1 to dZ_5. The air leaving dZ_6 will be assumed saturated so no drying occurs below the "zone."

Consider that the entire "zone of vaporization" lies in the bed at time "1." The amount of humidity gained by the air passing through the bed will be $1 + 2 + 3 + 4 + 4 + 4 = 18$ "humidity units." Consider that the entire "zone" is still in the bed at time "2" but that the bottom of dZ_6 is just at the bottom of the bed. The amount of humidity gained by the air will be $1 + 2 + 3 + 4 + 4 + 4 = 18$ "humidity units."

At time "3" the "zone" has moved even further down and now only dZ_1 to dZ_5 are in the column. The humidity of the air leaving is now only $1 + 2 + 3 + 4 + 4 = 14$ "humidity units." Consider that this process continues until the bed is completely dry (i.e., the "zone" is completely out of the column). The results are tabulated below. This explanation is set up such that the increments are of equal length and the "zone" moves at a uniform rate. Under these conditions, the time for each increment to completely leave the column will be equal.

Time	Increments in column	Humidity of exit air
1	$dZ_1 - dZ_6$	1+2+3+4+4+4 = 18
2	$dZ_1 - dZ_6$	1+2+3+4+4+4 = 18
3	$dZ_1 - dZ_5$	1+2+3+4+4 = 14
4	$dZ_1 - dZ_4$	1+2+3+4 = 10
5	$dZ_1 - dZ_3$	1+2+3 = 6
6	$dZ_1 - dZ_2$	1+2 = 3
7	$dZ_1 - dZ_1$	1 = 1

The above data are shown graphically in Fig. 2 of Plate II.

From Fig. 2 of Plate II it can be seen that as long as the entire "zone of vaporization" lies in the bed (A to B), the humidity of the air leaving is constant with $dH/dT = 0$. As the "zone" starts to leave the bed, the humidity starts to drop but as long as increments having an equal number of "moisture units" remain in the bed dH/dT remains at a constant value (B to C). When only increments having an unequal number of "moisture units" remain, the humidity continues to drop but dH/dT is no longer constant (C to D).

From this discussion, it may be seen that if an accurate plot of humidity as a function of time is made on the system from the time the "zone of vaporization" starts leaving the bottom of the bed until it has completely left the bed, the nature of the "zone of vaporization" itself may be evaluated.

EXPERIMENTAL STUDIES

Theoretical Approach

As stated in the section on Theory, the drying rate will be the rate at which the "zone of vaporization" moves through the column times a factor dependent on the amount of moisture removed from a given section during the complete passage of the "zone" through the section.

A drying cylinder was constructed with a series of thermocouples along the length of the tube. When air is passed downward through a bed of wet potatoes in the cylinder, a temperature gradient is set up. With the thermocouples it is possible to follow this temperature gradient as it moves through the column, hence, the rate of movement of the "zone" may be determined.

A sample of the wet potatoes fed into the drier was taken. When the temperature gradient indicated that the upper inch of the bed was dry, the run was stopped. At this point two samples were taken. Since the "zone" had passed entirely through the upper inch, this sample represented completely dried potatoes. Hence, this sample and the wet sample gave an indication of the amount of moisture removed in a section through which the "zone" had entirely passed.

The second sample taken was necessary for a material balance. Since the run was stopped before the "zone" had completely left the bed, some of the potatoes in the lower section of the drier were still wet. Hence, the second sample consisted of all the potatoes remaining in the drier after the first small sample had been taken.

A material balance was made on the potatoes removed from the drier to determine the amount of water removed during the drying period. The total amount of air flowing through the bed was known and the change in humidity of the air going through the bed as a function of time was known from humidity measurements on the air leaving the drier. Therefore, another material balance could be made on the air to determine the amount of water removed during the drying period.

The determination of the length of the "zone" was basically a matter of finding the vertical distance between points A and B in Fig. 2 of Plate I. However, since the length of the "zone" was generally very close to the depth of the bed, this calculation was complicated somewhat and is fully discussed in the section on Sample Calculations.

An attempt was made to evaluate the nature of the "zone" itself by following the humidity of the exit air from the drier. This was done with a piece of apparatus (Plates III and IV) such that the wet and dry bulb temperatures of the air could be determined at various time intervals.

Drying Equipment

In this section each piece of equipment used is described and its general specifications given together with the reasons for its use.

All equipment used in this investigation may be seen in Plates IV and V. The relative relationship of the operational equipment may be seen on the flow sheet (Plate III).

Air Source: Ordinary compressed air from the college power plant was used in the drying experiments. The pressure was

EXPLANATION OF PLATE III

Schematic flow diagram

A. Globe valve for control of air flow

B. Dehumidifier immersed in fifty percent ethylene glycol-water solution

C. Cooler

D. Heater

E. Six electric resistance elements

F. Thermostat

G. Device for measurement of temperature of air entering drier

H. Drier

I. Pinchclamps acting as valves

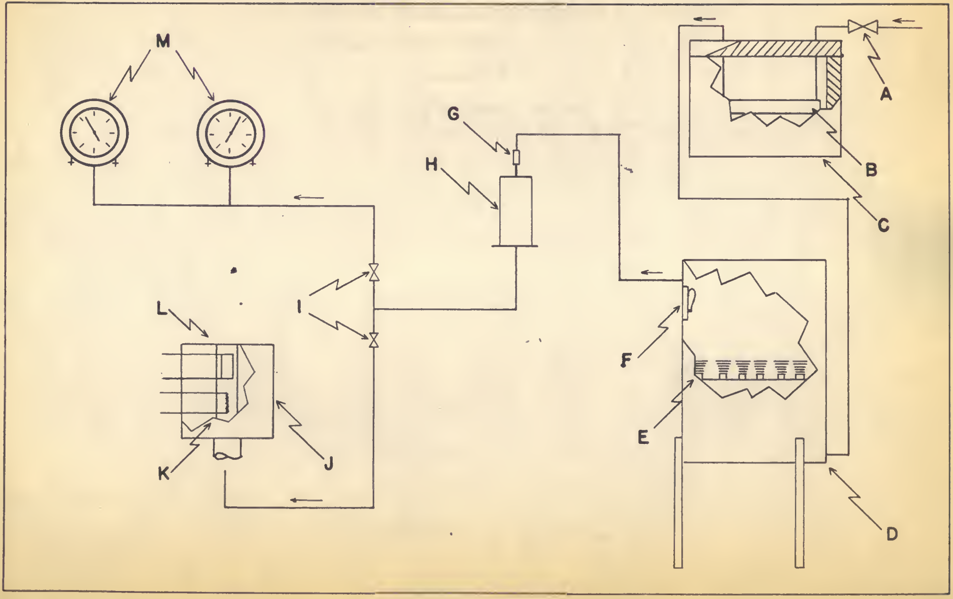
J. Exploded view of device for measurement of humidity of air leaving drier

K. Dry bulb thermocouple

L. Wet bulb thermocouple

M. Wet test meters for measurement of air flow

PLATE III



EXPLANATION OF PLATE IV

All operational equipment except the dehumidifier and heater

A. Two wet test meters for measuring total air flow

B. Thermocouple for determination of temperature of air entering drier

C. Twelve point multiple connector

D. Drier

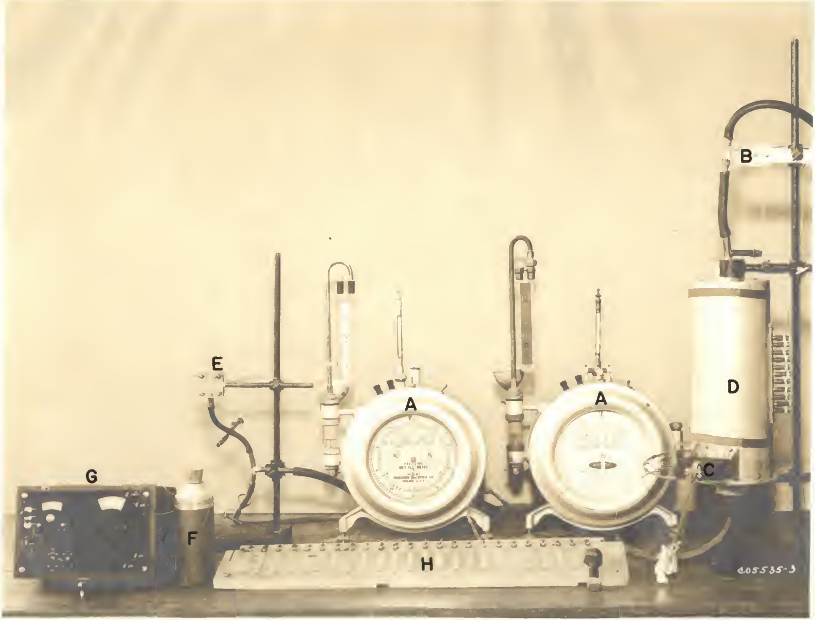
E. Thermocouples for determination of humidity of air leaving drier

F. Thermos bottle for cold junction

G. Potentiometer

H. Switchboard

PLATE IV



EXPLANATION OF PLATE V

Dehumidifier and heater

A. Cooler containing cooling medium

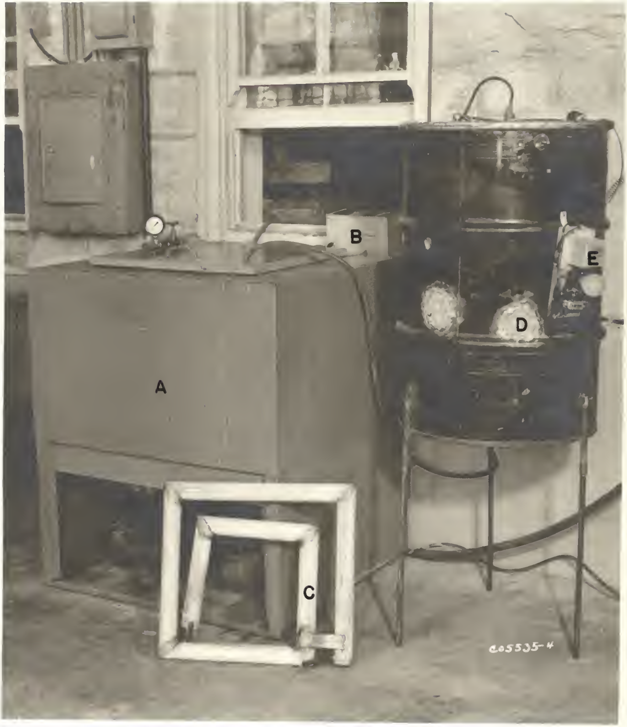
B. Transformer (220 to 110 volts)

C. Cooling coil of two inch diameter tubing (normally inside cooler during operation)

D. Heater

E. 110 to 24 volt transformer (for thermostat), indicator light and relay

PLATE V



controlled by a small globe valve to meet the conditions of the system.

Dehumidifier: The air was maintained at a low constant humidity by passing it through a dehumidifier. The dehumidifier consisted of approximately seven feet of two inch diameter galvanized tubing soldered into a "square spiral" arrangement as shown in Plate V.

This spiral was placed in the bottom of a cooler (Plate V) which was filled with a 50 percent (by volume) solution of water and ethylene glycol. After the cooler had been in operation about two hours, the outlet temperature of the air came to equilibrium at about 10° F.

Heater: The air heater (Plates III and IV), used to reheat the air after it left the condenser, consisted of a 50 gallon drum which contained six 1,000 watt resistance elements arranged linearly across the middle of the drum. The temperature of the air leaving the drier was controlled by a thermostat located inside the drum near the air outlet. The amount of heat given off during the "on period" of the thermostat cycle depended on the number of resistance elements in the circuit and how they were wired. For this work, all six elements were always in the circuit and were connected in a series-parallel arrangement (i.e., the elements were arranged so that groups of two were in series, while the three groups of two in series were in parallel). In order to get a uniform temperature inside the heater, a small fan was set at the bottom of the drum to keep the air circulating.

The thermostat was arranged in such a manner that its setting could be controlled by a screw from the outside. An indicator light served to show when the heating elements were in operation. The temperature of the outlet air was controlled to plus or minus 2° F. after the system came to equilibrium.

Inlet Air Temperature Thermocouple: This thermocouple (Plate IV) was placed in the air line between the heater and the drier at a position about six inches from the inlet of the drier. Its purpose was to give the temperature of the air entering the drier.

The arrangement consisted of a piece of lucite rolled into a tube with the thermocouple wires going through the side of the tube so that the sensitive junction was located on the axis of the tube (Plate VII). Short pieces of 3/8 inch diameter pipe were glued to the ends of this plastic tube and the tube was placed in the line by placing the rubber tubing over the pipe.

Drier: The drier (Plate VI) consisted of a 16 inch length of two inch diameter galvanized tubing with a screen at the bottom. Thermocouples were installed at one inch intervals along the length of the tube for a total length of 12 inches. The thermocouples were connected to the side of the tube by first wrapping the junction with one layer of "Scotch" tape and then securing this insulated junction to the tube wall by wrapping rubber tape around the circumference of the tube.

In order to minimize heat losses, the galvanized tube was insulated by placing it inside an aluminum shell, five inches

EXPLANATION OF PLATE VI

Schematic diagram of drier

A. Twelve thermocouples attached to tube (numbered as shown)

B. Rubber gasket

C. Removable top of drier

D. 2.0 inch diameter galvanized iron tube

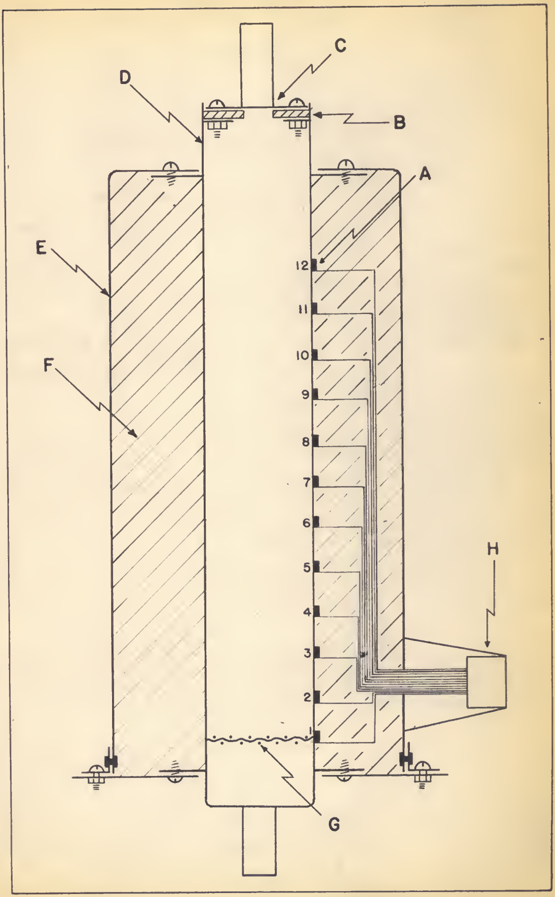
E. 0.026 inch thick aluminum outer shell

F. Vermiculite insulation

G. Screen

H. Twelve point multiple connector

PLATE VI



in diameter, and the annulus filled with vermiculite insulation. The drier was built so that the top could be removed for filling with potatoes and then replaced for the drying operation.

The air was fed into the top of the drier rather than the bottom to eliminate any fluidization effects. It was found that when the air was blown up through the bottom the wet bed as a whole had a tendency to lift and as drying occurred the individual particles would blow around in the drier. With this downflow arrangement the bed is held firmly against the screen by the pressure of the air.

To facilitate the handling of the drier the thermocouples were all connected to a 12 point multiple connector which simplified the removal of the drier from the electrical system. The removal of the drier from the mechanical system was accomplished by pulling off the inlet and outlet hoses.

Air Flow Metering: Slight variations in the pressure of the air from the powerhouse made it necessary to measure the total flow rather than merely to control just the flow rate. This was accomplished by the use of two wet test meters (Plates III and IV). Air leaving the drier went to a tee, one leg of which went to the humidity measuring equipment and the other to the wet test meters. Air leaving the first tee normally entered a second tee, both legs of which went to a wet test meter.

At the flow rate used, 1.5 $ft.^3$ per minute, it was found that one wet test meter lacked the capacity to record the entire flow rate, so two were used. These wet test meters were in constant operation except when humidity readings were being made.

Humidity Measurement: This measurement was made by use of a device (Plates III and IV) quite similar to the inlet air temperature thermocouple. In this device, however, there were two thermocouples--one above the other. The lower thermocouple acted as the dry bulb thermocouple while the upper one, which had the junction wrapped with filter paper, acted as the wet bulb. The air, diverted from the wet test meters, entered at the bottom of this device and was expelled to the atmosphere. Before each reading, the wet bulb was moistened with one or two drops of water from an eye-dropper. The diameter of the tube was such that the air passed the thermocouple at a velocity of about 25 feet per second.

Switchboard: Due to the extensive use of thermocouples, it was necessary to have some sort of switchboard to control the signal into the potentiometer. The switchboard (Plate IV) consisted of a board 28 inches long with 24 aluminum strips (only 15 of which were used) on it. The strips were raised on one end by being nailed to a 1/4 inch strip. The circuit was closed by putting a weight on the strip which would close the desired circuit. A diagram of the entire thermocouple system is shown in Plate VII.

Miscellaneous: The thermocouple readings were made on a Leeds and Northrup potentiometer (Model No. 3657-C). The cold

EXPLANATION OF PLATE VII

Schematic diagram of thermocouple system

- - - - - - - Iron wire

__________ Constantan wire

A. Wet bulb thermocouple of humidity measuring device (thermocouple No. 13)

B. Dry bulb thermocouple of humidity measuring device (thermocouple No. 14)

C. Thermocouple for measuring temperature of air entering drier (thermocouple No. 15)

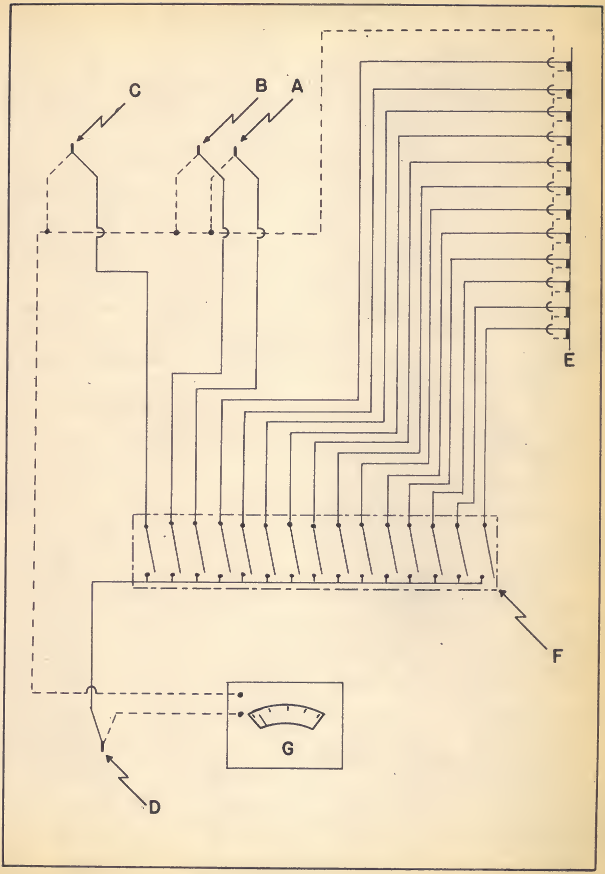
D. Reference junction (32° F.)

E. Twelve thermocouples on column

F. Switchboard

G. Leeds and Northrup potentiometer

PLATE VII



junction was a small thermos bottle filled with ice. All thermocouples were iron-constantan.

Experimental Procedure

Preparation of Potatoes: This method is a modification of the method of preparation presented by Bostock (2).

All potatoes used in this investigation were of the Red McClure variety purchased as needed at various grocery stores. For this reason data as to maturity, length of storage, etc. were not available.

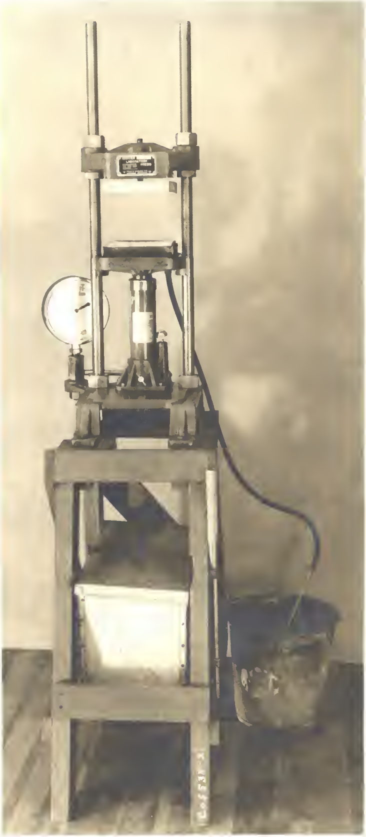
A batch of about five pounds of potatoes was peeled, halved and cooked in a pressure cooker for a period of 20 minutes at a gage pressure of five pounds per square inch. After the cooking was completed, the pressure cooker was placed under a stream of cold tap water until the cooker became cool. Upon cooling, the potatoes were removed from the cooker and placed in a tray in a freezer and frozen at a temperature of 0° F.

When a run was to be made, the potatoes were removed from the freezer and placed in a stream of air at room temperature for approximately 1.5 hours. At the end of this thawing time the potatoes were dewatered. The dewatering consisted of wrapping several thawed potatoes in a heavy nylon filter cloth and subjecting them to 8,000 pounds per square inch pressure in a hydraulic press (Plate VIII). This pressure removed enough water to get the potatoes down to a moisture content of approximately 60 percent (wet basis). This dewatering was done to

EXPLANATION OF PLATE VIII

Press for dewatering potatoes

PLATE VIII



remove water and to get the potatoes to a moisture content at which the potato particles possessed relatively little stickiness.

Miscellaneous Preparation Prior to Run: About half an hour prior to the actual start of the run, the heater and dehumidifier (Plate III) were placed in operation at about the desired air flow rate to allow the equipment to come to equilibrium by the time the run itself started. Also the thermos bottle for the cold thermocouple junction was filled with ice and all the equipment except the drier was connected.

Loading the Drier: As soon as the desired amount of potatoes had been dewatered the drier was filled. The operation was performed using the apparatus shown in Plate IX. The potatoes were formed into granules of the desired size by rubbing them through a stainless steel screen of the appropriate mesh. As the potato particles left the screen they fell directly into the drier. This method was used in order to minimize any packing effect, since at this moisture content the potato particles are very compressible and any handling tends to form them into a compact mass. After filling the drier completely to the top, the upper end of the column was anchored in place. At this point some of the potatoes which had adhered to the sides of the filling apparatus were collected as a wet sample for determination of moisture content of the inlet potatoes.

Drying: After the drier was filled, it was placed in position for the run (Plate IV), the necessary electrical and mechanical connections made, and the run started. Five minutes

EXPLANATION OF PLATE IX

Arrangement for granulating potatoes and filling drier

A. Screen in position for granulation

B. Funnel attached to bottom of board with hole in center

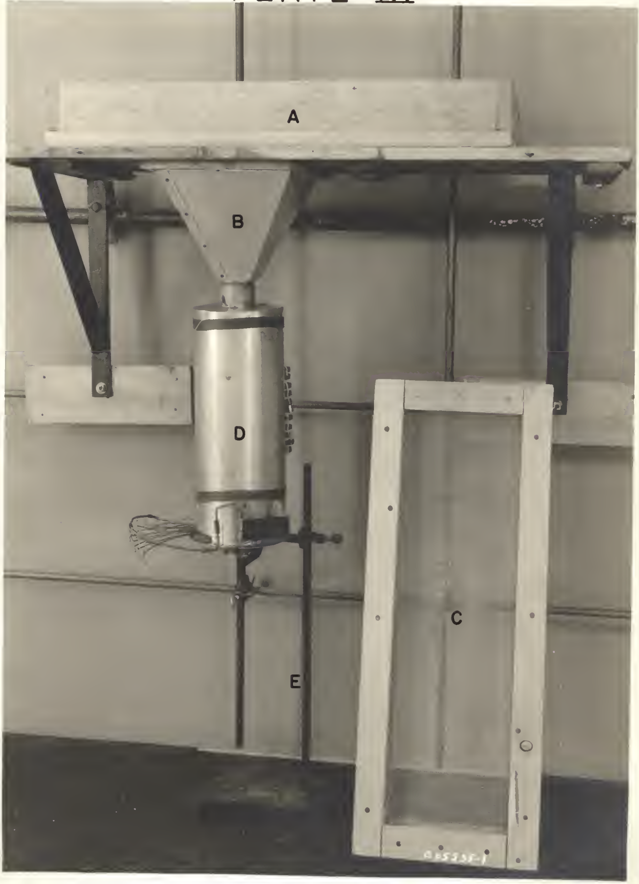
C. Screen (top view)

D. Drier ready for loading

E. Ringstand holding drier to funnel

Potatoes are granulated through screen (A) by hand and drop into funnel (B) and then into drier.

PLATE IX



after the run had begun the following temperatures were recorded:

1) The temperature of the inlet air to the drier (T.C. 15)
2) The twelve temperatures along the length of the drier (T.C. 1-12)
3) The wet and dry bulb temperature of the air leaving the drier (T.C. 13 & 14)

Readings were made at appropriate intervals (usually every half hour). The rate of air flow was metered by the use of two wet test meters in parallel on the outlet of the drier. After each reading, the wet test meters were checked to determine if the flow rate had been at the desired value during the previous time interval. If not, the necessary corrections were made. These wet test meters were in constant operation during a run except when the air was diverted from them to the humidity measuring equipment.

Humidity measurement consisted of opening the air line to the humidity equipment and then closing the line to the wet test meters. These humidity readings usually required about 30 seconds and were made immediately after each set of temperature readings.

Operations After Run: At the conclusion of a run the top of the drier was removed and two samples of the potatoes taken. The first sample was taken by emptying the top inch of potatoes from the column into a weighing pan. The second sample consisted of all the remaining potatoes which were placed into a large weighing pan. The moisture contents of the three samples (including the initial wet sample) were gravimetrically determined by drying for approximately eighteen hours in a vacuum (25" Hg) oven at 160° F.

INTERPRETATION OF RESULTS

In this study there was one basic variable, i.e., the size of the granule being dried. The flow rate of the air through the bed was kept constant at about 1.5 ft.^{3}/minute, at a temperature of 90° F. and at an inlet humidity of about seven grains of H_2O per pound of dry air. Three preliminary runs were made at a flow rate of about 0.75 ft.^{3}/minute which was found to be too low for drying measurements.

Plate X shows a plot of rate of "zone" movement vs. expected particle diameter. The term expected particle diameter refers to the expected diameter which would result from granulating the potatoes through a screen of such a mesh that would give a particle of this diameter if the resulting particle were spherical and just went through the screen opening.

As mentioned previously, each increment of the "zone of vaporization" is characterized by a temperature. The rate at which any one temperature goes through the column is then equal to the rate at which the "zone" moves through the column. The rate of "zone" movement was calculated on the basis of the rate at which a temperature of 80° F. went through the column (see sections on Theory and Sample Calculations). The selection of 80° F. was arbitrary.

EXPLANATION OF PLATE X

Plot of rate of temperature (80° F.) movement through column vs. expected particle diameter.

A. Least squares regression line for points shown

B. Ninety-five percent confidence limits on means

C. Ninety-five percent confidence limits on individuals

PLATE X

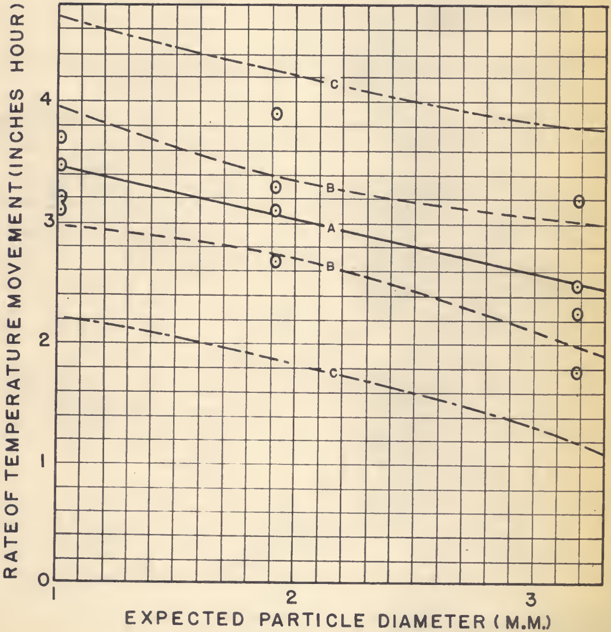

RATE OF TEMPERATURE MOVEMENT (INCHES HOUR)
0
1
2
3
4
C
B
A
B
C
1
2
3
EXPECTED PARTICLE DIAMETER (M.M.)

Plate X significantly indicates that as particle size increases the "zone" moves through the column at a decreasing rate. The least squares regression line (A) shown for the data may be expressed in the following form:

$R_z = 3.91 - 0.44D$

Where:

R_z = rate of "zone" movement (inches/hr.)

D = expected particle diameter (m.m.)

The calculation of the amount of moisture removed from a dried section involved the bulk density of the potatoes in the drier. This value was determined by calculating the weight of wet potatoes filling the column which is of a known volume. These values of the bulk density of wet uncompressed granules are plotted vs. "expected particle diameter" as shown in Plate XI. A discussion of the subject of compressed and uncompressed potato granules is presented later in this section. The least squares regression line for the points shown may be expressed as follows:

$\rho_B = 0.246 - 0.018D$

Where:

ρ_B = Bulk density of granules when wet (approximately 60 percent water - wet basis) and uncompressed (gms./c.c.)

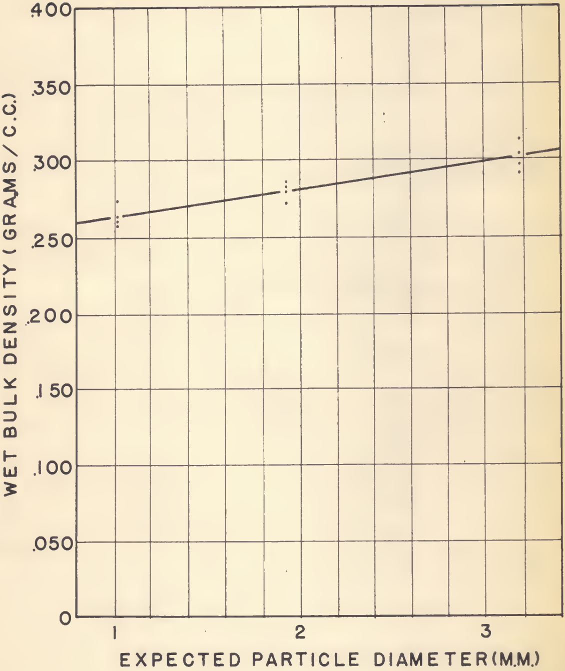
D = Expected particle diameter (m.m.)

Combining the rate of "zone" movement with amount of moisture removed from a section gave the rate of water removal. These results are seen graphically in Plate XII. Since the

EXPLANATION OF PLATE XI

Plot of wet bulk density of potatoes (based on a full column before any settling or compression effects have occurred) vs. expected particle diameter

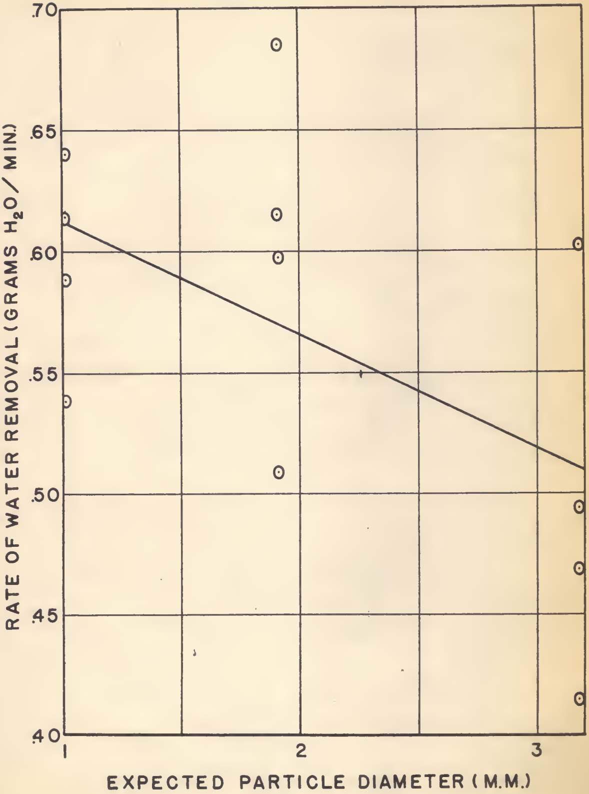
PLATE XI


WET BULK DENSITY (GRAMS / C.C.)
.400
.350
.300
.250
.200
.150
.100
.050
0
1
2
3
EXPECTED PARTICLE DIAMETER (M.M.)

EXPLANATION OF PLATE XII

Plot of drying rate vs. expected particle size with the least squares regression line for the points shown

PLATE XII


.70
.65
.60
.55
.50
.45
.40
RATE OF WATER REMOVAL (GRAMS H_2O / MIN.)
1
2
3
EXPECTED PARTICLE DIAMETER (M.M.)

values of rate of "zone" movement showed considerable variation, these points are also rather widely spread. A least squares regression line through these points indicates that as particle size increases the rate of water removal decreases. These results may be expressed as:

$R_{wr} = 0.663 - 0.049D$

Where:

R_{wr} = rate of water removal (gms./min.)

D = expected particle diameter (m.m.)

These results are in agreement with the work of Marshall and Hougen (5) who through-dried extruded zinc oxide and found that increasing diameter decreased drying rate.

The previous equation would not be very useful for design work of any kind so the data were recalculated into the form shown in Plate XIII (weight of feed dried per hour vs. expected particle diameter). The equation resulting from the correlation shown is:

$R_f = 71.8 - 5.4D$

Where:

R_f = Rate at which wet feed is dried (gms. feed/hr.)

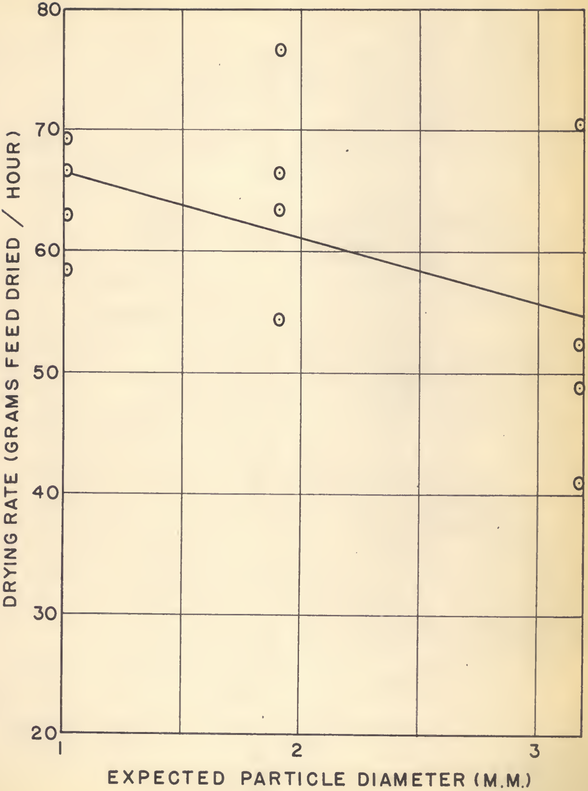
D = Expected particle diameter (m.m.)

Calculations on the length of the "zone of vaporization" indicate that the length of the "zone" may be independent of particle size. The data on the length of the "zone" is summarized below:

EXPLANATION OF PLATE XIII

Plot of grams of wet feed dried per hour vs. expected particle diameter

PLATE XIII


80
70
60
50
40
30
20
1
2
3
DRYING RATE (GRAMS FEED DRIED / HOUR)
EXPECTED PARTICLE DIAMETER (M.M.)

Expected particle diameter (m.m.)	Average "zone" length (in.)
1.01	10.03
1.91	10.15
3.18	10.34

The above data would seem to indicate that the length of the "zone" tends to increase as the expected particle diameter increases. However, there is so much variation from run to run for the four runs comprising each average that statistically there is no relation between particle diameter and "zone" length on the basis of these data.

There were three preliminary runs which did not have adequate moisture content data for determination of the drying rate but did have the temperature data necessary for the length of the "zone" to be calculated. These runs were made at half the air flow rate of the main body of runs and for these runs it was found that the length of the "zone" was no different from the length of the "zone" found at higher flow rates.

Allerton, et al did some through-drying work on a porous bed of non-porous particles and found the "zone" length of the order of the magnitude of 1/3 to 1/4 inch. For potato granules, this study had indicated a length of "zone" of the order of one foot. The length of the "zone" may be considered as the length of bed needed to saturate the entering air. The work of Allerton, et al was with non-porous particles and hence the drying was of the nature of evaporation from a free liquid surface and very little length of bed was necessary to saturate the air.

Due to the dissimilarity between the velocity of drying air and particle size used in this study and the one made by Allerton, et al a comparison of the two is not entirely feasible.

It might be expected that a relationship would exist between drying rate and length of "zone." As the rate of water removal (drying rate) increases, the length of bed required to saturate the air ("zone") might be expected to decrease. An attempt was made to verify this by a plot of rate of water removal vs. length of "zone." However, the points fell in such a wide scatter that it was unlikely that any conclusions could be drawn from them.

An attempt was made to determine the nature of the "zone of vaporization" from the humidity data. The humidity data were also used for material balances. These humidity material balances gave the amount of water removed during drying to within plus or minus 15 percent of the amount determined by a material balance on the potatoes removed from the column. However, it was found that there was too much discrepancy between the plots of humidity of outlet air vs. time, from run to run, to evaluate the nature of the "zone." It is felt that the method of evaluating the humidity lacks the necessary sensitivity required for an accurate study of this nature.

The drying rate determined by this method is primarily dependent on the rate of "zone" movement. A statistical analysis on the data was made and is shown on Plate X. This statistical analysis was felt to be necessary since the values of rate of "zone" movement showed considerable variation for a given value of expected particle diameter. It is believed that some of this was due to a possible variation in the bulk density from run to run.

At the beginning of a run the column was filled to the top with wet potatoes. At the end of a run when the top of the column was removed, it was always noted that the level of the potatoes had dropped considerably. This drop was attributed to shrinkage of the potatoes. After the main body of data had been taken, it became evident that very little of this drop was due to shrinkage. The drop in level was mainly due to compression of the wet bed due to pressure drop through it.

To partially correct for this a run was later made to determine the magnitude of this effect. It was determined that when the air was first applied the bed started to compress. Somewhere between one and two minutes after the run began, the bed ceased compressing and remained at virtually the same volume for the remainder of the run. The bed was initially 14 inches in depth when the top was placed on it. After the bed had stopped compressing, it was 10 inches in depth.

It was also noted that when the granules had been placed in the drier any shock such as would occur in handling also tended to reduce the volume of the bed since the method of filling the column left a very loose packing.

An example may serve to illustrate this point. Consider a bed of material being dried. Consider that the bed is 10 inches long, the "zone of vaporization" is very short (so that the length of the "zone" may be neglected) and the air drying the material is of such a nature that the material will be dried in 10 hours. Since the "zone" must entirely traverse the bed, the "zone" will move at a rate of one inch per hour. Now consider that the bed is compressed to only five inches in length while having the same moisture content and amount of material as before. Again since the same amount of moisture must be removed the drying time will be 10 hours. However, this time the rate of "zone" movement will be one-half inch per hour. Hence, any variation in the depth of the bed from run to run will affect the rate at which the "zone" moves through it.

When the runs were made, the importance of this effect was not realized and in many cases the bed may have been compressed more than four inches. When a run was made the drier was filled and placed in position for the run but the inlet air line was not connected. The air flow was started at a rate approximately equal to the desired flow rate through bed when the drier was placed in the line. The drier was then placed in the system and the flow rate was brought to the desired value. In some instances it is possible that the initial flow rate may have been higher than the desired one and hence more compression of the bed may have resulted. The compression of four inches was determined from data on a run that was started at a very slow flow rate and then brought up to the desired flow rate to prevent any of this "overcompression."

Plate X shows two sets of confidence limits. The inner set of limits on means and the outer set is on individuals. For the limits on means the chances are 95 out of 100 that the true average rate of movement falls within the limits shown for any given value of expected particle diameter. For the limits on individuals a similar statement holds for the true rate of movement for an individual run with a given value of expected particle size.[1]

The equations for these confidence intervals are as follows:

$$C.I._{95}(\text{means}) = \hat{Y} \pm (sy.x)(t_{95})\sqrt{\frac{1}{n} + \frac{(X-\bar{X})^2}{\sum x^2}}$$

$$C.I._{95}(\text{individuals}) = \hat{Y} \pm (sy \cdot x)(t_{95})\sqrt{1 + \frac{1}{n} + \frac{(X-\bar{X})^2}{\sum x^2}}$$

(See Statistical Calculations for a complete explantion of the symbols.)

In the above equations $\hat{Y}$ represents the estimated value of Y (in this case rate of movement) corresponding to a given value of X (expected particle size). $s_{y.x}$ represents the standard deviation from regression and it is unlikely that further runs would change its value much from the one it has for these data.[2] t_{95} is a constant dependent on the number of runs but even then it is practically a constant.

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[1] Doctor H. C. Fryer - Personal Communication.
[2] Doctor H. C. Fryer - Personal Communication.

For the interval on means, the quantity under the square root sign would decrease quite a bit as the number of runs increased. This would result in a narrowing of the confidence interval.

For the limits on individuals, the function of sample size under the radical has a one added to it, and hence, increasing the number of runs would do very little to narrow down the confidence interval.

In the event that these data were to be used for design work of any sort, it would be necessary to use a safety factor that would include all possibilities. It is not sufficient to just base the safety factor on the confidence interval on means but it must be based on the confidence interval on individuals since if one individual were to have a rate of movement slower than the unit was designed for serious consequences would result and this would be quite likely if the confidence interval or mean was used as a basis for the safety factor.

It was stated previously that it is rather unlikely that $s_{y \cdot x}$ would be changed very much with an increase in the number of runs. This holds true if more runs of a similar type were made. At the time the runs were made it was not known what factors were causing the rather wide variations in the points (and high value of $s_{y \cdot x}$) and therefore it was decided that from a practical viewpoint, since $s_{y \cdot x}$ and the confidence interval on individuals could not be reduced much, that an increased number of runs was not justified.

SUMMARY OF RESULTS

The main variable studied was the effect of particle size on the rate of drying of potato granules which are being through-dried. It was concluded from this study that the rate of drying decreased as particle size increased. This is in agreement with other work on through-drying. It was also shown that the length of the "zone of vaporization" may be independent of particle size and flow rate of the drying air. It also appeared that there was a good deal of variation in drying rate from run to run for a given "expected particle size," however, the increasing trend in drying rate as particle size decreased was quite evident.

This study has shown that, while some refinements are undoubtedly necessary, this method of determining drying rates for through-drying is a satisfactory one. The equipment for the determination of the humidity of the air leaving the drier lacked sufficient sensitivity to give accurate enough data for the determination of the nature of the "zone of vaporization."

RECOMMENDATIONS FOR FUTURE WORK

For actual design calculations on a pilot plant drier using the principles of through-drying, it would be desirable to have data on the other variables affecting the drying rate, i.e., air flow rate and temperature of the inlet air.

An exact idea of the changes occurring in each "increment" of the "zone of vaporization" itself might well be the starting point for the determination of the mechanisms involved in the drying of potatoes. To this end, it would be well to work on a very accurate method of determining humidity of the air leaving the drier.

It is felt that a great deal of the variation in the rate of "zone" movement through the column may be due to a non-uniformity of bulk density from run to run. Also, some shrinkage occurs during drying. Another factor responsible for this spread may be the fact that there were insufficient points on the temperature gradient to get an exact idea of the true nature of the gradient. This would be due to a lack of sufficient thermocouples on the column. Also, use of a more sensitive temperature measuring device might be invaluable.

There, for a thorough investigation into the possibilities of this method of determining drying rates, the following changes are recommended.

1) The material to be dried should be such that no compression or shrinkage could occur (e.g., carefully screened pumice soaked in water).
2) Use a column having perhaps two or three thermocouples per inch.
3) Use a more sensitive temperature measuring device.

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APPENDIX

OUTLINE OF CALCULATIONS

Nomenclature:

1) Wet potatoes: Potatoes at the moisture content at which they were fed into the drier.
2) Dry or dried potatoes: Potatoes at the moisture content they would be after being processed by the drier (i.e., a moisture content lower than that of the potatoes fed but higher than bone dry).
3) Bone dry potatoes: Potatoes which have a zero moisture content.

1) Calculation of water removed based on the weight of dried potatoes removed from drier at the end of a run:

The dried potatoes removed from the drier were split into two parts. A small portion from the top of the drier is placed in a small weighing pan as the "dried sample," the remaining potatoes in the drier are placed in a larger weighing pan and are termed "remaining sample." These two samples are taken because the upper section of the potatoes is completely dried while the remainder is still not quite dry.

Having the weight of dried potatoes removed from the drier and the moisture content changes that have occurred during drying, the amount of water removed during drying is calculated.

2) Calculation of water removed based on humidity:

A knowledge of the humidity changes of the air going through the drier as a function of time and the amount of air going through the drier during the run gives an alternative method of determining the amount of water leaving the drier. Having this value, a check may be made on the amount of air removed as calculated in (1).

3) Calculation of rate at which the "zone of vaporization" moves through the column:

This forms the basis of the calculation for the rate of drying and is explained in detail in calculation (13).

4) Calculation of drying rate:

Having the bulk density (ρ_B) of the wet potatoes fed into the drier, the weight of wet potatoes in the uppermost one inch section of the bed may be calculated. Since the final weight of dried potatoes remaining in this section may be found, it is possible to calculate the amount of water removed from this section. (This upper one inch section is used because it is a portion of the potatoes that is completely dried.) Combining the amount of water removed with the rate at which the "zone of vaporization" moves through the column, the drying rate can be found.

5) Calculation of the length of the "zone of vaporization":

This has been previously discussed in section on Theory and also in calculation (20).

Sample Calculations

All calculations are for Run IV

Necessary data:

1. The temperature data given on page 81
2. The moisture content data on page 84
3. The humidity data on page 86
4. The air leaving the wet test meter was at 70° F. and was assumed saturated with $H = 0.0253$ # mole H_2O / # mole dry air.
5. The air entering the drier had a humidity of $H = 7$ grains H_2O/# dry air.

1) Moisture content of undried sample:

Wet weight = full weight - empty weight

$= 16.4007 - 6.3725 = 9.5282$

Dry weight = dried weight - empty weight

$= 10.9417 - 6.3725 = 4.0692$

Moisture weight = wet weight - dry weight

$= 9.5282 - 4.0692 = 5.4590$

Percent H_2O (wet basis) = (moisture weight/wet weight) 100

$= \frac{5.4590}{9.5282} = 57.3\%$

Gm. H_2O/gm. D.S. = moisture weight/dry weight

$= \frac{5.4590}{4.0692} = 1.342$

2) Weight of dried potatoes removed from drier

= weight in dried sample + weight in remaining sample

$= 7.48 + 116.8 = 124.28$

3) Weight of bone dry potatoes from drier

$$= \frac{\text{weight of potatoes removed from drier}}{\dfrac{\text{weight of dried potatoes}}{\text{unit weight D.S.}}}$$

$$= \frac{124.28}{0.519-1} = 81.82 \text{ gms.}$$

4) Weight of wet potatoes fed into drier

= (weight of bone dry potatoes from drier)

$$\left(\frac{\text{weight wet potatoes}}{\text{unit weight bone dry potatoes}}\right)$$

$= (81.82)(1.342 + 1) = 191.622$

5) Weight of moisture removed by drying

= weight wet potatoes fed in - weight dry potatoes removed

$= 191.622 - 124.28 = 67.342$ gm. H_2O removed

6) Mean humidity of air leaving drier - humidity of entering air

$$= \frac{\text{graphical integration of plot of humidity vs. time (Plate XIV)}}{\text{total time}} -$$

humidity of entering air

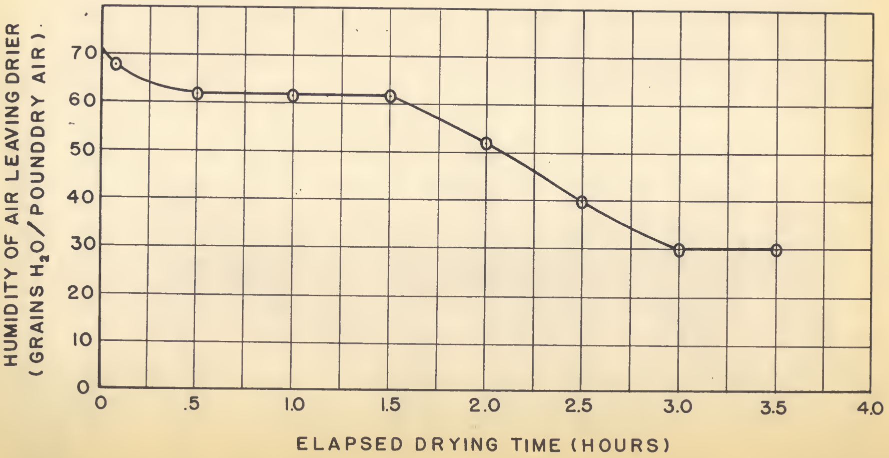
$= 49 - 7 = 42$ grains $H_2O/\#$ dry air

$= 0.00966$ # moles of $H_2O/\#$ moles dry air

EXPLANATION OF PLATE XIV

Plot of humidity of air leaving drier vs. elapsed drying time (Run IV)

PLATE XIV


HUMIDITY OF AIR LEAVING DRIER
(GRAINS H_2O/POUNDDRY AIR).
70
60
50
40
30
20
10
0
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
ELAPSED DRYING TIME (HOURS)

7) Total moles of saturated air leaving wet test meters

$$= \frac{\text{total volume of air leaving wet test meters}}{\text{volume of one mole of gas at operating temperature and pressure}}$$

$$= \frac{(3.5)(1.516)(60)}{359 \times \frac{460 + 70}{492}} = 0.823 \text{ moles wet air}$$

8) Total moles of dry air leaving wet test meters

$$= \frac{\text{total volume wet air leaving wet test meters}}{\frac{\text{moles wet air}}{\text{moles dry air}}}$$

$$= \frac{0.823}{0.0253 + 1} = 0.803 \text{ \# moles dry air}$$

9) Total moles of wet air leaving drier - moles water entering drier

= (total moles dry air leaving wet test meter) [(mean humidity leaving drier - humidity entering drier) + 1]

$= 0.803\ (0.00966 + 1) = 0.811$ # moles

10) Total moles of water removed from potatoes

= (total moles wet air leaving drier - total moles water in air entering drier) - total moles dry air

$= 0.811 - 0.803 = 0.008$ # moles H_2O

11) Total weight of water removed from potatoes

= total moles water removed x molecular weight

$= (0.008)(18)(454) = 65.376$ gms. H_2O removed

12) Material balance deviation

$$= \frac{\text{weight } H_2O \text{ removed (based on humidity)} - \text{weight } H_2O \text{ removed (based on dried potatoes removed)}}{\text{weight } H_2O \text{ removed (based on dried potatoes removed)}} \times 100$$

$$= \frac{65.376 - 67.34}{67.34} \times 100 = -2.92\%$$

13) Rate at which temperature gradient moves down column:

This value is determined by making a plot of temperature vs. time (Plate XV) for the thermocouples 4 - 8. From this plot the time at which each thermocouple reached 80° F. may be determined. These values are given below.

Thermocouple	Time required to reach 80° F. (hrs.)
8	0.825
7	1.000
6	1.375
5	1.700
4	1.900

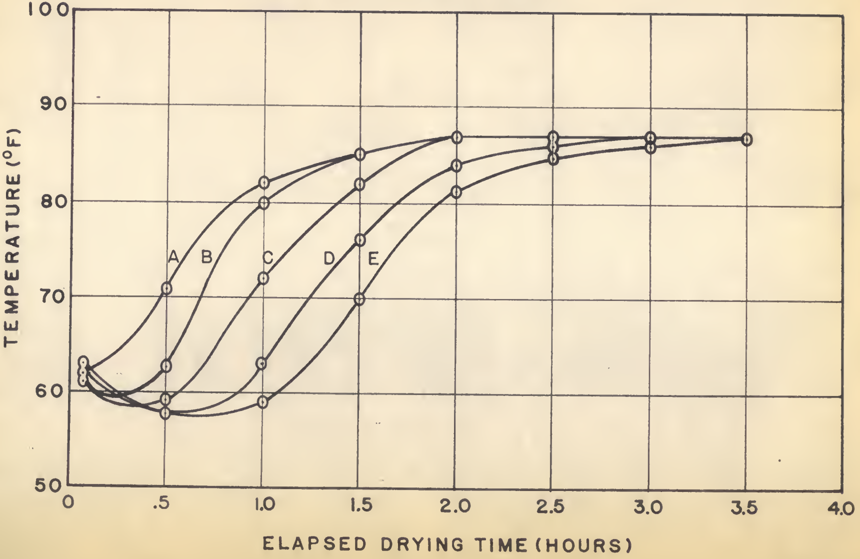
The values given above may be plotted (Plate XVI) as thermocouple number vs. time. Theoretically the points should fall in a straight line but since this was rarely the case, a straight line was fitted to it using the method of least squares (see following section of Statistical Calculations). Since these thermocouples were placed one inch apart, the resulting slope gives the rate at which the gradient moved through the bed in in./hr. For this run, the value was found to be b = 3.467.

EXPLANATION OF PLATE XV

Plot of temperature vs. elapsed drying time for thermocouples four through eight (Run IV)

A. Thermocouple 8
B. Thermocouple 7
C. Thermocouple 6
D. Thermocouple 5
E. Thermocouple 4

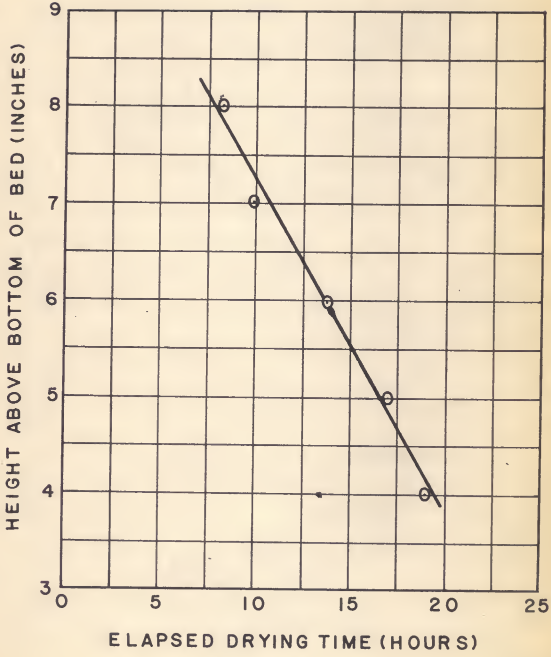
PLATE XV


100
90
80
70
60
50
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
TEMPERATURE (°F)
ELAPSED DRYING TIME (HOURS)
A
B
C
D
E

EXPLANATION OF PLATE XVI

Plot of position above the bottom of the bed vs. the time that position reached a temperature of 80° F. The straight line is the least squares regression line for the points shown (Run IV)

PLATE XVI


HEIGHT ABOVE BOTTOM OF BED (INCHES)
9
8
7
6
5
4
3
0
5
10
15
20
25
ELAPSED DRYING TIME (HOURS)

14) Bulk density of wet sample:

The drier was filled to the top with wet potatoes. This means the volume occupied was 722 c.c. From a previous calculation (4), the weight of wet potatoes fed is found to be 191.62 gms.

$$\rho_B(\text{wet}) = \frac{191.62}{722} = 0.265 \text{ gms./c.c.}$$

However, previous discussion has indicated that during the run itself the actual volume has been decreased due to the compression effect caused by the pressure drop and hence the bulk density must be corrected for this change in volume.

Length of bed before compression = 14 inches

Length of bed after compression = 10 inches

$$\rho_B(\text{wet and corrected}) = 0.265 \times \frac{14}{10} = 0.371 \text{ gms./c.c.}$$

15) Weight of wet potatoes in one inch section of drier

$= \text{volume (c.c./one inch section)}(\rho_B)$

$= 51.6 \times 0.371 = 19.15$ gms. wet potatoes

16) Weight of bone dry potatoes in one inch section

$$= (\text{weight wet potatoes}) \frac{\text{weight bone dry potatoes}}{\text{unit weight wet potatoes}}$$

$$= \frac{19.15}{1.342 + 1} = 8.19 \text{ gms. bone dry potatoes}$$

17) Weight of dried potatoes remaining in this section

$$= \frac{\text{weight bone dry potatoes in this section}}{\frac{\text{weight dried potatoes}}{\text{unit weight D. S.}}}$$

$= 8.19\ (0.045 + 1) = 8.55$ gms. dried potatoes

18) Weight water removed from this section

= weight potatoes in - weight potatoes out

= 19.15 - 8.55 = 10.60 gms. H_2O removed/inch

19) Rate of water removal

= (slope (b))(water removed/inch)

= (3.467 in./hr.)(10.60 gms. H_2O removed/in.)
(1 hr./60 min.)

= 0.614 gms. H_2O removed/min.

20) Rate of drying of wet material

= (amount of wet material dried/in.)(rate of "zone" movement (in.hr.))

= (19.15)(3.467) = 66.50 gms./hr.

21) Length of "zone of vaporization":

It is assumed that the length of the "zone" is the distance between the point of lowest temperature and the point of highest temperature. However, the length of the "zone" was generally found to be very close to the length of the bed such that at the time the lowest temperature was near the bottom, the final dried temperature was not yet inside the column. However, by knowing (a) the position of the lowest temperature (T_L) at time "1", (b) the position of the high temperature (T_H) at time "2", and (c) the rate at which the gradient goes through the column, it is possible to calculate the length of the "zone" as follows:

From the temperature data on page 81, at 10:30 it is found that the T_L(57° F.) is at thermocouple position 3.

Two hours later T_H(87° F.) first appeared at thermocouple position 5. Thus, two hours after the lower end of the "zone" was at position 3, the top end of the "zone" was at position 5, two inches above position 3 while the entire "zone" was moving at a rate of 3.467 in./hr.

Length of "zone" = 2 x 3.467 + 2.0 = 8.934 in.

Statistical Calculations

1) Calculation of least square regression coefficient for the rate of temperature movement through the drier.

The data: (from calculation (13))

X	Y
.825	8
1.000	7
1.375	6
1.700	5
1.900	4

$$b \text{ (slope)} = \frac{\Sigma xy}{\Sigma x^2}$$

$$\Sigma xy = \Sigma(XY) - \frac{(\Sigma X)(\Sigma Y)}{n}$$

$$\Sigma x^2 = \Sigma(X^2) - \frac{(\Sigma X)^2}{n}$$

Where: Σ = summation

n = number of points being considered

$$\Sigma xy = 37.95 - \frac{(6.80)(30.0)}{5} = -2.85$$

$$\Sigma x^2 = 10.07 - \frac{(6.80)^2}{5} = 0.822$$

$$b = \frac{\Sigma xy}{\Sigma x^2} = \frac{-2.85}{0.822} = -3.467$$

The slope (b) goes through the X and Y means of 1.36 and 6.0.

2) Calculation of regression coefficient used to correlate rate of "zone" movement with expected particle diameter (shown in Plate X).

The data:

X (particle diameter m.m.)	Y (rate in./hr.)
1.01	3.69
1.91	3.29
3.18	3.20
1.01	3.47
1.91	3.89
3.18	2.27
1.01	3.10
3.18	2.49
1.91	3.11
3.18	1.78
1.91	2.68
1.01	3.20

$\Sigma X = 24.4$ $\qquad \Sigma Y = 36.16$

$\Sigma X^2 = 59.1224$ $\qquad \Sigma Y^2 = 113.010$

$\Sigma XY = 69.3304$

$$\Sigma y^2 = 113.010 - \frac{(36.16)^2}{12} = 4.0479$$

$$\Sigma x^2 = 59.1224 - \frac{(24.4)^2}{12} = 9.5091$$

$$\Sigma xy = 69.3304 - \frac{(24.4)(36.16)}{12} = -4.195$$

$$b = \frac{-4.195}{9.5091} = -0.4412$$

This value of (b) passes through the X and Y means of 2.03 and 3.01.

3) Calculation of 95 percent confidence limits on the mean value of rate of temperature movement for a given value of particle size.

$$C.I._{95} = \hat{Y} \pm (sy \cdot x)(t_{95}) \sqrt{\frac{1}{n} + \frac{(X - \bar{X})^2}{\Sigma x^2}}$$

$$sy \cdot x = \sqrt{\frac{\Sigma y^2 - \frac{(\Sigma xy)^2}{\Sigma x^2}}{n - 2}}$$

Where:

$\hat{Y}$ = value of rate found from the curve on Plate X

$\bar{X}$ = mean value of X

X = X coordinate of the point at which $\hat{Y}$ was estimated

$C.I._{95}$ = 95% confidence limits

$sy \cdot x$ = standard deviation from regression

t_{95} = a constant depending on the number of points and probability level being used (in this case, 95%)

From the preceding calculation the value of Σx^2, Σy^2, and $sy \cdot x$ are found:

$$sy \cdot x = \sqrt{\frac{4.0479 - \frac{17.5980}{9.5091}}{10}} = 0.4688$$

For the point where X = 1.01 and Y = 3.44: (From Plate X)

$$C.I._{95} = 3.44 \pm (0.4688)(2.228) \sqrt{\frac{1}{12} + \frac{(2.03 - 1.01)^2}{9.5091}}$$

$$= 3.94 \text{ and } 2.94$$

By similar calculations:

X	$C.I._{95}$
2.03	3.36 and 2.71
3.05	3.04 and 2.08

4) Calculation of 95 percent confidence limits on individual values of rate for a given value of particle size. This calculation is the same as for the preceding one except that the function of sample size under the radical has a one added to it.

$$C.I._{95} = \hat{Y} \pm (sy.x)(t_{95}) \sqrt{1 + \frac{1}{n} + \frac{(X - x)^2}{\Sigma x^2}}$$

The resulting data are:

X	C.I.$_{95}$
1.01	4.71 and 2.21
2.03	4.20 and 1.82
3.05	3.81 and 1.31

5) Calculation of 95 percent confidence limits on the true slope of the least squares regression line (A) in Plate X.

$b = -0.4412$ (slope of line A - Plate X)

$s_{y.x} = 0.4688$ (from calculation 3)

$\Sigma x^2 = 9.5091$

$$s_b^2 = \frac{(s_{y.x})^2}{x^2} = \frac{(0.4688)^2}{9.5091} = 0.02311$$

$s_b = 0.152$

$$C.I._{95} = -0.4412 \pm (t_{95})(s_b)$$
$$= -0.4412 \pm 0.3336$$
$$= -0.7798 \text{ to } -0.1026$$

6) Calculation of approximate number of runs necessary to give 95 percent confidence limits on true slope of line A - Plate X to ± 0.0583.

$$\text{C.I.}_{95} = -0.4412 \pm 0.0588$$
$$= -0.4412 \pm (t_{95})(s_b)$$

Assuming that t_{95} is approximately 2.00 and that $s_{y.x}$ does not change due to increasing runs

$$(t_{95})(s_b) = 0.0588$$

$$s_b = \frac{0.0588}{t} = \frac{0.0588}{2.228} = 0.0294$$

$$s_b^2 = 0.000864$$

$$s_b^2 = \frac{(s_{y.x})^2}{\Sigma x^2}$$

$$\Sigma x^2 = \frac{(s_{y.x})^2}{s_b^2} = \frac{(0.04688)^2}{0.000864} = 254.4$$

If all the new runs are made such that only the same three values of the expected particle diameter are used and that at each of these values there are the same number of Y values, Σx^2 will be linear with the number of runs. For 12 runs $\Sigma x^2 = 9.5091$.

$$\frac{9.5091}{12} = 0.7924 \text{ units of } \Sigma x^2/\text{run}$$

$$\text{Number of runs} = \frac{254.4}{0.7924} = 321 \text{ runs}$$

Actually the value of t_{95} used was only an approximation of the correct value but this calculation gives an approximate idea of the necessary number of runs.

Calculated data

Run:	I	II	III	IV	V	VI
1) Expected particle diameter (m.m.)	1.01	1.91	3.18	1.01	1.91	3.18
2) Flow rate (ft.^{3}/min.)	1.51	1.54	1.51	1.52	1.56	1.44
3) Wet weight potatoes fed to drier (gms.)	187.4	202.2	219.8	190.1	196.6	214.5
4) Weight water removed by drying (gms.) (based on weight dried potatoes removed from drier)	57.1	68.4	70.6	66.7	96.2	98.1
5) Weight water removed by drying (gms.)(based on humidity)	---	73.6	65.4	65.4	74.9	95.6
6) Bulk density of wet uncompressed potatoes (gm./c.c.)	0.259	0.279	0.304	0.265	0.272	0.297
7) Rate of temperature movement through bed (in./hr.)	3.69	3.29	3.20	3.47	3.89	2.27
8) Rate of water removal (gm./min.)	0.640	0.597	0.602	0.614	0.635	0.469
9) Drying rate (gms. feed dried/hr.)	69.2	66.4	70.5	66.5	76.5	48.6
10) Length of "zone of vaporization" (inches)	12.38	10.58	10.40	8.93	9.78	12.54

Calculated Data (continued)

Run:	VII	VIII	IX	X	XI	XII
1) Expected particle diameter (m.m.)	1.01	3.18	1.91	3.18	1.91	1.01
2) Flow rate ft.^{3}/min.)	1.42	1.56	1.54	1.51	1.55	1.50
3) Wet weight potatoes fed to drier (gms.)	138.4	20916	203.6	230.6	202.4	196.6
4) Weight water removed by drying (gms.) (based on weight dried potatoes removed from drier)	60.3	79.7	62.8	81.4	69.3	58.4
5) Weight water removed by drying (gms.)(based on humidity)	65.4	73.6	61.3	70.3	63.3	49.0
6) Bulk density of wet uncompressed potatoes (gm./c.c.)	0.261	0.290	0.282	0.319	0.280	0.273
7) Rate of temperature movement through bed (in./hr.)	3.10	2.49	3.11	1.78	2.68	3.20
8) Rate of water removal (gm./min.)	0.538	0.494	0.615	0.415	0.509	0.588
9) Drying rate (gms. feed dried/hr.)	58.4	52.4	63.5	41.1	54.5	63.0
10) Length of "zone of vaporization" (inches)	9.00	9.98	10.22	8.45	10.02	9.80

Temperature (°F.) Readings for Run I

T.C. No.	1	2	3	4	5	6	7	8	9	10	11	12	15
Time													
9:30					Start of Run								
9:35	66	63	63	63	63	63	63	66	73	85	88	88	100
10:00	60	59	58	59	59	61	65	74	81	83	84	84	90
10:30	58	56	56	57	61	68	76	80	81	83	83	83	90
11:00	58	57	60	68	76	81	82	83	84	84	84	84	90
11:30	63	67	72	79	82	84	84	84	84	84	84	84	90
12:00	71	77	80	83	84	85	85	85	85	85	85	85	90
12:30	77	81	83	85	86	87	88	88	88	88	88	88	91
1:00	79	81	84	85	87	88	88	88	88	88	88	88	91

Temperature (°F.) Readings for Run II

9:05					Start of Run								
9:35	66	60	58	59	59	59	59	62	71	76	83	83	91
10:00	60	58	57	56	59	59	65	74	80	82	83	83	90
10:30	59	56	57	60	67	75	81	83	85	85	85	85	90
11:00	60	59	63	73	78	82	83	85	85	85	85	85	91
11:30	67	71	75	81	84	85	86	86	86	86	86	86	92
12:00	74	77	81	84	85	86	87	87	88	88	88	88	90
12:30	77	82	84	86	87	88	88	88	88	88	88	88	90
1:00	80	82	84	86	87	88	88	88	88	88	88	88	90

Temperature (°F.) Readings for Run III

9:30					Start of Run								
9:35	72	68	67	75	61	63	63	64	69	78	82	84	93
10:00	63	60	60	59	60	61	64	72	81	84	85	86	90
10:30	62	59	59	59	63	71	80	83	84	86	86	86	90
11:00	62	60	62	67	76	81	84	86	86	88	88	88	90
11:30	66	68	73	80	84	86	86	88	88	88	88	88	90
12:00	73	75	79	83	85	87	88	88	88	88	88	88	90
12:30	78	81	83	85	87	88	88	88	88	88	88	88	90
1:00	81	84	85	87	88	88	88	88	88	88	88	88	90

Temperature (°F.) Readings for Run IV

T.C. No.	1	2	3	4	5	6	7	8	9	10	11	12	15
Time													
9:30					Start of Run								
9:35	70	67	64	63	62	61	61	62	67	77	82	83	93
10:00	61	59	58	58	58	59	63	71	80	84	85	85	90
10:30	60	58	57	59	63	72	80	82	84	86	86	86	90
11:00	61	59	62	70	76	82	85	85	87	87	87	87	90
11:30	67	71	77	81	84	87	87	87	87	87	87	87	90
12:00	76	80	83	85	86	87	87	87	87	87	87	87	90
12:30	79	83	85	86	87	87	87	87	87	87	87	87	91
1:00	81	84	85	87	87	87	87	87	87	87	87	87	91

Temperature (°F.) Readings for Run V

9:30					Start of Run								
9:35	66	64	62	61	60	60	60	60	64	72	80	81	93
10:00	61	59	58	58	58	59	62	69	79	82	84	85	90
10:30	60	57	57	59	63	70	77	81	84	85	85	85	90
11:00	61	61	63	70	74	81	84	85	87	87	87	87	90
11:30	67	72	74	80	83	84	86	87	87	87	87	87	90
12:00	74	80	82	84	86	87	87	87	87	87	87	87	90
12:30	80	83	84	85	87	87	87	87	87	87	87	87	90
1:00	82	84	85	86	87	87	87	87	87	87	87	87	90
1:30	83	85	85	87	87	87	87	87	87	87	87	87	90
4:30	83	85	85	87	87	87	87	87	87	87	87	87	90

Temperature (°F.) Readings for Run VI

9:00					Start of Run								
9:35	67	63	63	63	62	62	61	61	63	63	70	79	93
10:00	60	59	58	58	57	57	57	59	65	74	80	81	90
10:30	59	57	56	56	56	57	61	67	76	81	83	83	90
11:00	59	56	56	56	59	66	73	78	82	84	84	84	90
11:30	59	56	57	63	69	75	80	83	84	84	84	84	90
12:00	60	60	65	73	77	79	83	84	84	84	85	85	90
12:30	66	69	73	75	81	83	84	85	85	85	86	86	90
1:00	71	77	79	82	83	84	85	85	86	86	86	86	90
1:30	75	80	81	84	84	84	85	85	86	86	86	86	91
2:00	77	81	82	84	84	85	85	85	86	86	86	86	90
2:30	77	81	82	84	84	85	85	85	86	86	86	86	90

Temperature (°F.) Readings for Run VII

T.C. No.	1	2	3	4	5	6	7	8	9	10	11	12	15
Time													
1:30	Start of Run												
1:35	64	63	62	60	60	60	60	60	63	71	77	78	90
2:00	56	55	55	55	55	57	57	57	71	77	79	79	90
2:30	56	54	54	54	56	60	67	74	77	79	80	80	90
3:00	56	54	56	60	63	74	78	81	81	82	83	83	90
3:30	57	59	62	71	76	79	81	82	82	83	83	83	90
4:00	61	67	71	76	79	81	81	82	82	83	83	83	90
4:30	68	74	77	80	81	81	82	82	83	83	83	83	90
5:00	70	75	77	81	81	81	82	82	83	83	83	83	90

Temperature (°F.) Readings for Run VIII

12:15	Start of Run												
12:20	69	65	64	61	60	60	59	59	59	63	71	77	90
12:45	61	58	57	56	56	57	58	62	70	78	83	84	91
1:15	60	57	56	56	56	60	66	74	80	83	84	84	91
1:45	59	56	56	59	63	71	77	81	84	84	85	85	90
2:15	60	59	61	68	74	80	82	84	85	85	85	85	90
2:45	63	67	70	77	80	83	84	85	86	86	85	85	90
3:15	76	74	76	80	82	84	84	85	85	85	85	85	90
3:45	74	77	79	81	83	84	84	85	85	85	85	85	90

Temperature (°F.) Readings for Run IX

1:30	Start of Run												
2:00	60	57	57	57	57	57	59	65	76	81	84	84	90
2:30	59	56	56	56	58	63	71	78	83	84	84	84	90
3:00	60	57	59	62	70	77	83	84	85	86	86	86	90
3:30	63	63	66	74	80	84	84	86	86	86	86	86	89
4:00	68	70	75	81	84	85	86	86	84	84	84	84	89
4:30	73	76	79	82	84	86	86	86	86	86	86	86	90

Temperature (°F.) Readings for Run X

T.C. No.	1	2	3	4	5	6	7	8	9	10	11	12	15
Time													
12:30	Start of Run												
12:35	70	67	65	63	61	61	60	60	60	62	70	77	91
1:00	60	57	56	56	56	56	56	58	67	74	81	82	90
1:30	59	56	56	55	56	60	67	74	81	83	84	84	91
2:00	59	56	56	57	60	69	75	79	82	84	84	84	90
2:30	60	58	59	63	67	77	81	81	84	84	84	84	90
3:00	60	62	64	72	77	80	82	83	84	84	84	84	90
3:30	66	67	72	77	80	83	85	85	85	85	85	85	90
4:00	72	74	77	81	83	84	85	86	85	85	85	85	90

Temperature (°F.) Readings for Run XI

6:30	Start of Run												
6:35	69	66	64	62	60	59	59	60	63	70	77	78	90
7:00	59	57	56	56	56	56	59	64	76	81	84	84	90
7:30	58	56	56	57	57	66	76	81	84	85	85	85	90
8:00	59	56	57	64	72	77	83	84	82	87	87	87	90
8:30	60	62	67	74	80	82	84	84	82	87	87	87	90
9:00	67	73	77	81	83	84	85	86	87	87	87	87	90
9:30	71	74	77	81	83	84	85	86	87	87	87	87	90

Temperature (°F.) Readings for Run XII

12:30	Start of Run												
12:35	66	64	61	59	58	58	58	60	68	76	80	81	90
1:00	59	56	56	55	56	56	61	73	80	83	84	84	90
1:30	59	55	56	58	64	73	80	83	85	86	86	86	90
2:00	60	60	63	70	77	81	84	86	86	86	86	86	90
2:30	66	70	74	80	83	84	86	86	86	86	86	86	90
3:00	74	78	81	84	84	85	86	86	86	86	86	86	90

Moisture Content Data

Run	Sample	Pan No.	Empty Wt.	Full Wet Wt.	Dried Wt.	% H_2O	gm.H_2O/gm.D.S.
I	Undried	6	6.8725	18.7675	11.8887	57.46	1.35
	Dried	8	6.8284	14.9665	14.6057	4.45	.0465
	Remaining		89.1	211.3	166.4	36.7	.581
II	Undried	6	6.8725	20.8423	12.9939	56.18	1.282
	Dried	8	6.8284	14.3330	13.9865	4.62	.0484
	Remaining		89.1	215.4	173.0	33.6	.51
III	Undried	6	6.8725	19.9970	12.9703	53.0	1.15
	Dried	8	6.8284	14.7027	14.3426	4.6	.048
	Remaining		89.1	230.5	186.1	31.4	.46
IV	Undried	6	6.8725	16.4007	10.9417	57.3	1.334
	Dried	8	6.8284	14.3127	13.9913	4.3	.045
	Remaining		89.1	205.9	166.0	34.16	.519
V	Undried	6	6.8725	21.0061	13.2032	54.5	1.20
	Dried	8	6.8284	14.0933	13.9477	2.0	.0204
	Remaining		89.1	182.2	172.0	10.95	.123
VI	Undried	6	6.8725	19.0190	11.8330	59.16	1.45
	Dried	8	6.8284	13.9675	13.7066	3.65	.038
	Remaining		89.1	198.4	171.3	24.79	.330

Moisture Content Data (continued)

Run	Sample	Pan No.	Empty Wt.	Full Wet Wt.	Dried Wt.	% H_2O	gm.H_2O/gm.D.S.
VII	Undried	6	6.8725	17.5452	11.4748	56.88	1.319
	Dried	8	6.8234	14.1266	13.8554	3.716	.0366
	Remaining		89.1	209.9	165.7	36.59	.577
VIII	Undried	6	6,8725	21.0326	12.7762	58.31	1.40
	Dried	8	6.8284	14.5031	14.2039	3.90	.0406
	Remaining		89.1	211.4	171.3	32.79	.488
IX	Undried	6	6.8725	20.4140	12.2227	59.68	1.48
	Dried	8	6.8284	14.6961	14.4377	3.28	.034
	Remaining		89.1	222.0	166.6	41.635	.715
X	Undried	6	6.8725	22.9900	16.1175	62.04	1.635
	Dried	8	6.8284	13.2828	13.0069	4.27	.0446
	Remaining		89.1	231.3	172.6	41.28	.703
XI	Undried	6	6.8725	20.9903	12.9061	57.26	1.34
	Dried	8	6.8284	15.4624	15.2633	2.306	.024
	Remaining		89.1	213.6	170.0	35.02	.539
XII	Undried	1	15.7669	30.0137	21.3085	57.59	1.36
	Dried	11	15.8200	23.7097	23.4087	3.815	.0397
	Remaining		219.6	350.2	293.3	39.74	.66

Humidity Data

Run:	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Time after run start (hrs.)											
5 min.	66	70	68	68	82	66	63	--	72	70	58
.5	58	64	62	68	67	64	62	58	62	62	54
1.0	58	65	62	68	63	56	62	58	62	59	58
1.5	58	63	62	68	63	58	60	58	58	56	54
2.0	58	65	52	58	63	52	58	58	53	54	48
2.5	44	46	40	44	55	47	53	45	53	46	46
3.0	34	36	30	38	50	36	44	34	43	40	
3.5	27	34	30	31	42	31	32		40		
4.0				26	33						
4.5				26	26						
5.0					20						

Humidity of air leaving drier uncorrected for humidity of air entering drier (grains H_2O/# dry air)

A NEW METHOD OF
EVALUATING THE THROUGH-DRYING
CHARACTERISTICS OF POTATOES

by

JAY JOHN SCHELDORF

B.S., University of Illinois, 1953

AN ABSTRACT
OF A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE COLLEGE
OF AGRICULTURE AND APPLIED SCIENCE

1954

Through-drying is a little used but quite efficient method for drying a granular material. There appears to be no published data on this method as applied to the preparation of dehydrated potato granules.

There were two main objectives in this study. The first was to evaluate some of the through-drying characteristics of potato granules for possible use in a pilot plant scale dehydrator. The main variable studied was the effect of particle size on through-drying rates and the length of the "zone of vaporization." The second objective was to determine the effectiveness of a new method of evaluating the aforementioned drying characteristics.

As dry air is blown through a bed of wet granular material, a "zone of vaporization" is set up. This "zone" may be best visualized as a length of bed required for the saturation of the dry air entering the bed. Each portion of the "zone" is characterized by a temperature (which is constant for a constant flow rate, humidity and temperature of the entering air). As drying proceeds, this "zone" (and its temperature gradient) moves through the column.

The rate at which drying occurs is merely the rate at which the "zone" moves through the column times a factor which is dependent on the amount of moisture removed from a portion of the material as the "zone" moves entirely through this portion.

The rate of "zone" movement was determined by the use of a column to which twelve thermocouples were attached. Wet potatoes were placed in this column and dry air blown through it. The rate of "zone" movement was determined from the rate of movement of the temperature gradient set up in the "zone."

As air passes through the dried portion of the bed, its temperature remains constant. As this air enters the top of the "zone," its temperature starts to drop due to the evaporation of water. The air leaving the bottom of the "zone" is considerably cooler than the entering air and this temperature remains virtually constant as the now saturated air passes through the wet bed and out of the column. The length of the "zone" is merely the depth of bed between the point where the air begins to cool and that at which it becomes no cooler.

Each "increment" of the "zone" contributes a given amount of moisture to the final saturation of the air. Data on the humidity of the outgoing air from the drier as the "zone" leaves the bed would give an idea as to the nature of the "zone." Using a device to measure the wet and dry bulb temperatures of the air leaving the drier, an attempt was made to obtain this humidity data. It was found that this device lacked the sensitivity to give meaningful data.

This study has shown that for given inlet conditions of the drying air, the drying rate increases as the particle size decreases. This is in agreement with other work of a similar nature. Several runs were made at a lower flow rate than the main body of runs and these data indicate that the length of the "zone of vaporization" is independent of flow rate. The data from the main body of runs indicate that the length of the "zone of vaporization" may be independent of particle size within the range of sizes used in this study.